

Theme Report on Topic 10
EARTHQUAKE INSTRUMENTATION

by

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INTRODUCTION

The objectives of the present summary are to show the relationships between the work described in the contributed papers to each other and to the field in general. This becomes of some importance when it is realized that the relatively small number of ten submitted papers can only sample a few current instrumentation problems, and that many important aspects of the subject will not be formally presented but will need to be brought out in discussions. The present summary will draw attention to some of these missing subjects in the hopes of stimulating such discussions and of encouraging additional investigations.

One way of classifying the earthquake engineering instrumentation field is shown in the accompanying table, along with an indication of how the contributed papers of the present session fit into the picture. Measurements of either ground motion or of structural response have been influenced in such a critical way by the lack of knowledge as to the time and place of natural events that it is convenient to consider them separately from test events. For test events which occur at a previously known time and place, it is economically justifiable to provide more elaborate instrumentation systems, and to carry out the measurements with more care and attention from highly trained personnel. Since our present session has no papers touching on the special problems of test instrumentation, it is to be hoped that some of these problems will be taken up in connection with specific test programs to be described in other sessions of the conference. It should also be mentioned that a number of aspects of the earthquake instrumentation problem will be raised in Panel Discussion No. 1, "Earthquakes", under the heading 1.3, "Reliability of Records".

SUMMARIES OF GROUND MOTION PAPERS

The use of multiple seismoscopes as a direct response spectrum measurement has been pioneered in India, and the present status of the network of such structural response recorders there has been summarized by P. N. Agrawal. The basic characteristics of the device are given, and a location map is provided for the 68 recorders now installed. During the past decade, seven earthquakes have been recorded resulting in 80 records. The October 29, 1968 Koyna earthquake provided the first field check of the devices, and simultaneous measurements on an accelerograph and on a structural response recorder confirmed satisfactory behavior and accuracy. For two earthquakes, measurements were obtained at various locations, and plots of the results are given, showing the distribution of spectrum values. Some improvements in the design of the response elements

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are suggested, and recommendations are made for extended applications as a complement to time recording accelerograph installations.

M. D. Trifunac has shown in his paper how the usefulness of the structural response recorder readings can be extended by reference to past accelerograph measurements. The device discussed above by P. N. Agrawal contains six elements which trace out the horizontal response pattern of the ground motion corresponding to six points on the response spectrum - three periods of 0.40, 0.75 and 1.25 seconds, with two damping values each of 0.05 and 0.10 critical. M. D. Trifunac has calculated for each of the 186 ground accelerograms in the Caltech standard data bank of United States earthquakes the six horizontal response patterns corresponding to these values. In this way a background of structural response patterns becomes available which should greatly assist in an interpretation of future events recorded on this instrument. Based on these calculated responses to U.S. earthquakes, the author then proceeds to a statistical investigation of the way in which maximum response recorder readings correlate with Modified Mercalli intensity, soil classification, and near-field magnitudes. To the extent to which these U.S. data are applicable to other regions of the world, the results presented should considerably extend the amount of practical information which can be derived from this relatively simple and reliable device.

We consider next the description of the strong motion instrumentation network in Yugoslavia presented by V. Mihailov. Until recently, most of the strong motion networks in the world have of necessity developed in a haphazard manner. As instruments and sites become available, networks slowly expanded, sometimes in a way far from an optimum pattern. The Yugoslavian project was one of the first which was able to approach the installation of a sizeable network comprising now 136 accelerographs and 150 seismoscopes with a comprehensive plan of site location, areal distribution, balance of ground and structural installations, and an organized maintenance program. By considering during the network design stage the uses to which the measurements are to be put, such as determination of radiation paths, soil condition influences, and structural response determinations, it was possible to achieve a balance of capabilities which results in a more effective use of resources. Since the installation of the network a number of earthquakes have occurred for which useful accelerograms have been obtained. A tabular summary of eleven such events gives the main results and indicates that a highly satisfactory maintenance level has been achieved.

Turning next to an accelerograph network embodying many new concepts, we consider an evaluation report by J. Prince and F. H. Rodriguez on the telemetered seismic information system developed in Mexico. This pioneer effort represents in many respects the most advanced installation for strong ground motion measurements so far put in service. The system consists of 14 field stations involving five high sensitivity channels and 54 ground acceleration signals of various sensitivities extending over linear dimensions of some 150 kilometers. The transducer outputs are multiplexed and transmitted over six VHF radio links to a central station where they are continuously recorded. A data processing system involving A-D conversion and minicomputer data handling results in such basic output information as response

spectra in a matter of hours after an event. Experience with the system since it became operational in 1973 indicates that the routine daily checking of subcarrier frequencies has effectively forestalled such maintenance problems as low batteries, transmitter malfunctions, etc., and has minimized station down-time. Special studies have improved system behavior with respect to such factors as radio interference, lightning strokes, and other types of damage. To increase overall dynamic range, three gain levels of plus-minus 1.0g, 0.1g and 0.01g full-scale have been introduced in place of the original dual-gain system. Random radio interference proved to be a difficult problem and currently limits the achievable signal-to-noise ratio to 40 db relative to full scale. A tape speed compensation system has been introduced which considerably improved overall flutter and speed accuracy to figures compatible with the overall noise level. Data processing is based on electronic analog digital conversion, and optimum employment of both analog and digital filtering. The first test of the integrated system occurred in June 1976 when a $M = 6.3$ earthquake occurred at a distance of 320 kilometers. Within a few hours response spectrum calculations were complete for the most important acceleration components from five stations. Continued experience with the Mexican telemetered network will be followed with great interest by all earthquake engineers, since this approach is perhaps the most effective one so far suggested to achieve both rapid data processing and manageable field maintenance.

A final paper on the earthquake ground motion topic treats the important subject of early warning systems. T. Fujiwara presents the results on some interesting work on the problem of automatic train stopping during earthquakes. Since the locations of epicentral regions of strong earthquakes are known with respect to the particular high speed rail system involved with a good probability, it is feasible to use remote seismic sensing devices at some distance from the railway line towards probable epicenters. A second idea to increase the warning time margin for the initiation of train deceleration procedures is the prediction of the maximum amplitude of ground motion from the waveform of preliminary tremors. Statistical information is given on the relationship between the period of initial motions and the magnitude of the earthquake, and on the ratio between maximum motion and preliminary tremor amplitude. Best prediction was found when the maximum amplitude of preliminary tremors was used, but since this maximum often occurs near the end of the preliminary motion, the warning time in such cases would be too short. Additional studies are now being made to resolve such practical difficulties. A tripartite network of 25 kilometer separation with wire-telemetering data transmission and an on-line minicomputer has been installed to enable estimation of focus and magnitude immediately after an earthquake. These basic studies by the Japanese National Railways appear to be the most comprehensive approach so far made to the problem of automatic equipment shutdown for seismic hazard reduction, and the implications for many other applications such as elevators, power plants, etc., are obvious.

STRUCTURAL RESPONSE INSTRUMENTATION SUMMARIES

An example of a very extensive instrumentation system for measuring inputs and responses of various structures to earthquake excitation is provided by A. I. Martem'yanov, O. I. Ponomanov, and S. A. Federov* in their description of the U.S.S.R. Engineering Seismometric Stations. In addition to some 200 stations for seismological investigations, there has been in the U.S.S.R. since 1965-66 a growing E.S.S. network aimed at measuring strong earthquake motions induced in buildings, dams, bridges, etc. The authors summarize the present status of this E.S.S. network, which includes some 86 stations in industrial and civil buildings and an additional eight in hydroengineering structures. Each station consists of a number of transducers for measuring displacements, velocities, and accelerations at various locations within the structure and on the adjacent ground, recording at a central point. The stations are distributed at sites having differing soil properties, and are in buildings of various types and sizes. The largest number of building stations (39) are in buildings of 4-6 stories. Some intended developments of the instrumentation and network include: (a) provision of a larger number of instruments in some buildings to permit a detailed study of three-dimensional response. This requires a synchronization of records to 0.001 sec.; (b) provision of a 2 to 3 second memory in the recording system so that early arriving short period P wave induced motions can be recorded; (c) availability of a number of complete sets of mobile equipment for moving into epicentral regions for aftershock studies; and (d) development of new digital type instrumentation systems which should have many advantages over currently available analog types. Preliminary specifications for a proposed digital system involve a frequency range of 0-3 Hz, a dynamic range of 60 db, a sample frequency of 100 Hz, and a memory time of 2 seconds. The question of real-time storage of digital data is also discussed, with some comments on magnetic drum storage, displacement register techniques, ferrite-cube systems, and magnetic disk units. Some information is given on strong earthquakes recorded during 1970-76 at E.S.S. stations which have confirmed the effectiveness of the system.

The next paper to be considered touches on the important problem of system identification theory. P. C. Shah and F. E. Udawadia present an interesting analytical treatment of the problem of finding the optimum location of a sensor in a building structure to yield the maximum amount of information about the dynamic characteristics of the structure from input-output calculations. The particular example given is a building modelled as a fixed base undamped shear beam, and the question is the building height at which noisy strong motion records would result in the best estimates of distribution of building stiffness with height. A number of particular cases are investigated numerically, using as an input a scaled N-S component of the 1940 El Centro earthquake. The main results are that in the absence of prior knowledge a first floor level next to the basement input level yields the most information and is definitely better than a roof location. Although the optimum location cannot be solved exactly without some knowledge of stiffness distribution and of input motion, the results were found to be relatively insensitive to such factors, so that reasonable assumptions should lead to good results. As the amount of effort that goes into structural testing increases, it will clearly be of great importance to

* Refer theme 2-461

plan such investigations carefully, taking full advantage of results such as those given in the present paper.

Turning next to the subject of seismic instrumentation of special structures, we first mention the paper of W. Podolny and J. D. Cooper who report on the Highway Bridge Program of the U.S. Federal Highway Administration. In spite of the growing number of strong motion accelerographs in the United States, there has so far been no recording of a strong earthquake on a highway bridge. The program described involves twenty typical bridges across the United States instrumented to determine free-field motion, pier foundation response, superstructure response, and relative motion at such discontinuities as expansion joints, hinges, and abutments. The extent to which our past strong motion instrumentation has been limited to a small number of structural types has not always been fully appreciated, and many structures important to the life, safety, and well being of populations in seismic regions involve special problems for which little information is at hand.

Among the most critical seismic hazard problems are those associated with nuclear power plants. A paper by S. E. Pauly reviews the current status of strong motion earthquake instrumentation in nuclear facilities and summarizes plans for the near future. It is pointed out that there are now strong motion recording systems in use in over 50 power plants in several countries. In the United States, current regulations call for combinations of triaxial time history sensors, peak reading accelerometers, seismic switches, and response recorders. When expected foundation accelerations exceed 0.3g, additional instrumentation of the above type is required. There is also a standard specification for periodic instrument maintenance procedures which requires monthly channel checks, semi-annual channel functional tests, and channel calibrations at refueling intervals. A standard now under development will provide guidelines for retrieval, review, processing, and evaluation of records. A brief summary is also included of the nuclear power plant instrumentation policies of several other countries in seismic regions.

Also on the subject of earthquake instrumentation of nuclear power plants, the paper of D. S. Mehta and D. A. Godfrey brings to our attention the key role played by governmental regulations of the kind alluded to above. In the United States, earthquake instrumentation requirements for such plants are specified in official regulations coming from industry and from the federal government, as well as in standard review plans and safety analyses reports for nuclear power plants and for fuel reprocessing plants. Such regulations have recently been improved in the light of recorded seismic data. As the awareness of the importance of the seismic safety problem to public acceptance of certain energy options becomes more widely understood, it is to be expected that regulatory agencies of various kinds will take an increasingly active role in the detailed specification of instrumental requirements.

SOME CURRENT PROBLEMS

While the above ten papers have covered many important aspects of the subject, it is clear that many equally important matters have not been brought forward. It will perhaps be appropriate at this point to mention a few of these which have come to this reporter's attention.

(1) A number of newly developed instruments are now being deployed in strong motion networks and it would be interesting to have detailed information on them, including specifications, and the results of evaluation tests and of field experience. In the United States, for example, several central recording systems using multiple transducer packages are known to have been installed in structures in place of multiple individual accelerographs, and at least one digital magnetic tape accelerograph with a digital memory system has appeared on the commercial market.

(2) Several countries have much expanded their strong motion networks during the past few years, and valuable information on installation problems, field reliability, maintenance techniques, and data processing and dissemination should be available which would be advantageous for everyone.

(3) It would be useful to have an up to date summary of current world coverage by strong motion instrumentation. Are there still important seismic areas without adequate coverage? Could some of these areas be subjects for cooperative international efforts? How many instruments of what basic types would in fact be sufficient for given areas or for the world? What are the limiting factors in expanding the world network - instrument or installation cost, availability of trained maintenance personnel, data processing bottlenecks, etc.?

(4) There is a growing movement towards the installation of elaborate integrated instrumentation systems in large structural projects such as dams, bridges, power plants, etc. There has been some concern that the complexity of these major systems may in fact defeat some of the main objectives by reducing long term reliability. Records of performance and of field experience with some of these installations should now be available and would be of great assistance for the planning of new projects.

(5) To what extent and at what stage can instrumentation advances in other fields such as space exploration be transferred to earthquake engineering? Can recent major advances in integrated circuits, solid state data storage, and in minicomputer technology be expected to encourage new approaches in strong motion instrumentation and data processing in the near future?

(6) What are the possibilities for multipurpose instrumentation to serve both the seismologist and the earthquake engineer in view of certain basic incompatibilities of sensitivity, site condition, and frequency range? Absolute time can easily be added at a minor cost to strong motion accelerograms in most parts of the world by radio time signals, and the increased dynamic range that would be simply attained in digital systems would much enhance the capabilities of the strong motion accelerograph for seismological studies.

In conclusion, some speculations will be offered as to the reasons for the relatively small number of specialized instrumentation papers in this as in previous world conferences. First, instrumentation problems are usually very properly considered as steps along the way in a research investigation, the main object of which is to add to our knowledge of earthquakes rather than to our knowledge of instruments. Special studies of measurements will thus often form a part of or an appendix to a research paper. Secondly, the story of instrument development is often a record of troubles and failures. Nevertheless, an account of some of the missteps along the road to ultimate success may often be of great assistance to future investigators.

EARTHQUAKE ENGINEERING INSTRUMENTATION

⊗ - CONTRIBUTED PAPER, 6WCEE

	STRONG GROUND MOTION	STRUCTURAL INPUT AND RESPONSE
NATURAL EARTHQUAKES (TIME AND PLACE UNKNOWN)	<ul style="list-style-type: none"> MOTION-TIME RECORDERS TRANSDUCER DESIGN DIRECT READING ELECTRICAL-MECHANICAL FORCE BALANCE FEEDBACK TRIGGER SYSTEMS VERTICAL STARTERS MEMORY SYSTEMS TIMING SYSTEMS - ABSOLUTE TIME CALIBRATION AND CHECKOUT SIMPLIFIED RECORDERS SEISMOSCOPES DIRECT SPECTRUM DEVICES MULTIPLE SEISMOSCOPES ⊗ ⊗ REED GAGES PEAK READING DEVICES NETWORK DESIGN ⊗ INSTRUMENT TYPES ⊗ SEISMICITY STRUCTURAL SYSTEMS CENTRAL RECORDING TELEPHONE - HARD WIRE RADIO TELEMETRY ⊗ RELIABILITY MAINTENANCE REDUNDANCY REMOTE CHECK SITE INVESTIGATIONS WARNING SYSTEMS ⊗ REMOTE SENSING ALARM AUTOMATIC SHUTDOWN DATA PROCESSING RAPID READOUT FOR ACTION DIRECT READOUT MINIMUM EQUIP & TRAINING FIELD VS LABORATORY 	<ul style="list-style-type: none"> STRUCTURAL INPUT EXCITING FORCE OR MOTION FOUNDATION INTERACTION TORSIONAL EFFECTS STRUCTURAL RESPONSE MOTION VS STRAIN OPTIMUM SENSOR LOCATION SYSTEM IDENTIFICATION THEORY ⊗ CENTRAL RECORDING ⊗ MODE SHAPES TORSION SPECIAL STRUCTURES HIGH RISE BUILDINGS IRREGULAR BUILDINGS DAMS BRIDGES ⊗ POWER PLANTS ⊗ ⊗ SUPERVISORY EARLY WARNING & SHUTDOWN SOIL STRUCTURES LANDSLIDES LIQUIFACTION EARTH DAMS RETAINING WALLS CONSOLIDATION FOUNDATIONS INSTRUMENTATION TECHNIQUES ON-LINE REAL TIME COMPUTING TELEMETERED SYSTEMS DATA PROCESSING COMBINED LOADING - WIND
TEST EVENTS (SPECIFIED TIME AND PLACE)	<ul style="list-style-type: none"> NEAR FIELD MOTIONS SOURCE MECHANISM STUDIES WIDE RANGE RECORDING DYNAMIC AMPLITUDE RANGE NONLINEAR EFFECTS FREQUENCY RANGE HIGH STATION DENSITY LOCAL SOIL AND GEOLOGY TRANSMISSION PATH SPECIAL INSTRUMENTATION STRAIN DIRECT DISPLACEMENTS TORSION SITE INVESTIGATIONS 	<ul style="list-style-type: none"> FORCE GENERATION SINUSOIDAL VIBRATION EXCITERS ROTATIONAL LINEAR RANDOM VIBRATION EXCITERS MICROTREMOR EXCITATION MACHINERY PERSONNEL WIND INITIAL MOTION IMPACT BLAST PULL-BACK EXPLOSION GENERATED MOTIONS CHEMICAL H.E. NUCLEAR DELAY SEQUENCES VIBRATION TEST TABLES RESPONSE MEASUREMENTS TEST REPRODUCIBILITY COMPLETE COVERAGE LOCAL MEASUREMENTS DATA COLLECTION AND PROCESSING